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Damage functions for the cold regions and their applications in hygrothermal simulations of different types of building structures

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ABSTRACT

Several damage functions for the relative assessment of severity of environmental loads in cold regions based on the results of hygrothermal simulations are proposed. Considering their supposed use in the weather conditions involving freezing temperatures, the main attention is paid to the frost-induced damage. The designed functions are tested in a series of computational simulations carried out for several building envelopes composed of both contemporary and historical materials. The analyzed structures are exposed to three different weather data sets representing the average, critical and favorable conditions, and their hygrothermal response is utilized for the assessment of the damage functions under investigation. Recommendations for the practical application of the particular functions are given based on their sensitivity to the character of environmental load and the material composition and orientation of the envelope.

1. Introduction

The complexity of new and refurbished building envelopes has been growing over the last decades, adding new requirements to the design of both building envelopes and construction details. Therefore, not only structural but also other design aspects must be taken into account (e.g., durability, sustainability, energy efficiency), which turns the design process into a complex and multidisciplinary task (Langmans and Roels, 2014; Künzel and Zirkelbach, 2013, Suchorab et al., 2014). The primary objective of the hygrothermal design is to ensure healthy and comfortable place for the occupants, which must comply with the requirements for the energy efficiency. Last but not least, the serious hygrothermal design should ensure sufficient durability of the constructions in terms of their resistance to the environmental and climatic load (Kočí et al., 2012). It has been proven that long-term hygrothermal effect on durability of building materials needs to be taken into account (e.g., Maljaee et al., 2016, Lohonayi and Korany, 2013).

The exterior surface of building enclosures is exposed to various environmental effects that depend on the character of the environment. Such effects may cause biological, chemical, or physical degradation of the material. However, the estimation of each kind of degradation is a very complex task and the effects of the environment are significantly varying case to case, depending not only on the nature of the environment but also on the material composition. Therefore, the damage analysis is rather to be assessed by computational simulations than simple man-made estimation based on empirical knowledge. However, the computational simulations may provide the building envelope designers with the estimation of damage of wall assemblies only when the simulation results are supported by appropriate laboratory or field measurements. Nevertheless, even if the requirement for the experimental data is not met, the computational modelling can help assess the relative risk of environmental effects that arise due to climatic variations and construction practices (Mukhopadhyaya et al., 2006).

In order to quantify the effects induced to the construction, a specific function has to be introduced that is able to evaluate the severity of a particular environment with respect to the nature of the anticipated damage. Such a function is called the damage function. As it evaluates the severity of the environment, the damage function can be understood as a tool indicating the risk of possible damage or deterioration of the construction exposed to studied environment. The main objective of the damage function is to quantify the risk of deterioration into a single value. The indicated values can be then easily used for a comparative analysis of different weather loads on studied construction. The most popular damage functions describing the moisture induced damage is Time-of-Wetness (Corvo et al., 2008; Van den Bulcke et al., 2009; McCabe et al., 2013). Another damage function, the RHT–Index (Mukhopadhyaya et al., 2006) was designed for the assessment of excessive risk of deterioration as it quantifies the hygrothermal response or moisture management capacity of the wall assembly. The RHT-Index was used as a starting point for some newly derived damage functions presented in this paper. Some other damage functions were described by Salonvaara et al. (2010).

Frost-induced damage, which is the main topic of this paper, is typical for the regions with such weather conditions allowing the moisture retained in the materials to freeze (Li et al., 2015; Shi et al., 2016). At the

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evaluation of damage of building envelopes in the cold regions an ideal solution would consist in a formulation of a complex hygro-thermo-mechanical model including the dynamics of ice formation in the conditions of the porous space and other volumetric effects. Such approach would bring, though, increasing demands to input material parameters and, due to the complexity of the model, the overall computation time which might prove to be an uneconomic solution. More to that, such model needs to be supported by an extensive range of experimental and field measurements in order to be valid. However, the effect of the environment may be assessed on the comparative basis. For such an assessment a simple hygrothermal models can be applied using limited number of state variables. The result of such simulations can be assessed by specific damage functions working with the input data that comes directly from those models. For a comparison of different environmental loads or material variations such an approach would be, apparently, more convenient. However, the damage functions suitable for the regions characteristic by low temperatures, where frost damage of building structures takes place, are still rare in the scientific literature. The critical degree of saturation proposed by Fagerlund (1977a, 1977b) and the Winter Index introduced by Kočí et al. (2014a) belong to the few exceptions in that respect.

In this paper, several new damage functions for the analysis of hygrothermal simulation results are introduced which are aimed specifically at the application for cold regions. Then, these functions are tested using the comparison of results of year-long simulations of hygrothermal performance of various types of building enclosures exposed to average weather conditions given by the Test Reference Year (TRY), critical conditions given by 1996- and favorable conditions given by 2007- weather year of Prague, Czech Republic The critical and favorable years were selected from the weather year history of Prague using the approach introduced by Kočí et al. (2014a). Finally, the performance of each damage function is discussed with respect to the material composition of studied building enclosures and the type of environmental load.

2. Damage functions for the cold regions

In order to quantify a potential risk of frost induced damage to the studied wall assemblies a portfolio of several damage functions is introduced. Each damage function is described in this section and its performance is analyzed in the following sections. In the analysis of damage functions suitable or the cold regions, a modified version of the Winter Index (MWI) proposed by Kočí et al. (2014a) was used as a starting point. Contrary to the original research, where WI damage function was based on the input values in the form of temperature and relative humidity, in this paper MWI is defined as a cumulative function derived from temperature and moisture content distribution over a period of time for any specific area of the building envelope cross-section. MWI works with hourly values of temperature and moisture content and calculates the level of severity in the case that moisture content is above the prescribed critical level and simultaneously temperature drops below its critical value. Moreover, MWI is able to express the rate of exceeding the critical levels and thus, to indicate higher risk potential, as the severity is calculated for a particular point in the construction as

$$\mathrm{MWI} = \sum_{i=1}^{8760} (T_L - T_i)(w_i - w_L)\left[T_i < T_L \bigwedge w_i > w_L\right] \tag{1}$$

where T_L and w_L are critical values of temperature and moisture content and T_i and w_i are hourly values of temperature and moisture content, respectively. MWI is calculated only when both $T_i < T_L$ and $w_i > w_L$. Description of the critical values T_L and w_L is provided at the end of this section. The summation in Eq. (1) uses the Iverson bracket (Iverson, 1962), which is a notation that denotes a number that is 1 if the condition in square brackets is satisfied and 0 otherwise. In order to give T and w linear weight, it is more appropriate to express the moisture content in [% m^3/m^3]. Higher MWI values show greater potential for frost-related deterioration as they indicate higher crystallization pressure inside the pore space of the material. Standardly, the MWI is calculated for 365 consecutive days, therefore the upper limit in summation (Eq. (1)) is set to 8760 as the function process hourly data. However, in practical applications the upper and lower limits can be set freely according to the specific needs of investigation.

The newly introduced Time-of-Frost (TOF) damage function was inspired by the commonly used Time-of-Wetness damage function designed for the analysis of corrosion-related degradation (Corvo et al., 2008; Van den Bulcke et al., 2009; McCabe et al., 2013). TOF calculates the number of hours during the year when the conditions in the investigated point of the wall cross-section are favorable for ice formation, i.e., the temperature is below the critical temperature while the moisture content is above the critical value. TOF ranges between 0 and 8760; alternatively it can be expressed in %. Contrary to MWI, TOF returns integer number without taking into account the rate of exceeding the critical levels. TOF can be expressed as

$$\mathrm{TOF} = \sum_{i=1}^{8760} \left[T_i < T_L \bigwedge w_i > w_L\right] \tag{2}$$

with the same definition of critical values T_L and w_L (see end of this section).

Another proposed damage function, the Amount-of-Frozen-Water (AFW), returns the amount of liquid water retained in the investigated point under critical temperature during the year. AFW works with the assumption that when the temperature drops down below its critical level T_L, and liquid water is present in the material (i.e. $w_i > w_L$), whole amount of moisture in the investigated point is accounted for ice formation. Although such an assumption is not physically correct due to the fact that there is still some liquid water in the micro- and nanopores that remains unfrozen, the AFW may serve well for a comparative analysis. The higher value AFW returns, the more severe conditions occur in the investigated point in the wall assembly, which can lead to a faster degradation of the material in terms of frost damage. AFW works with the critical value of temperature only and formally can be expressed as

$$\mathrm{AFW} = \sum_{i=1}^{8760} w_i [T_i < T_L \wedge w_i > w_L]. \tag{3}$$

The number of indicative freeze/thaw cycles (IFTC) as the last damage function offered in this paper is a hypothetical number of freeze/thaw cycles that may occur in the investigated point in the wall assembly during the simulation year. The conditions for ice formation are based on critical values of temperature and moisture content as in MWI. In order a freeze/thaw cycle to be found valid, the freezing must take at least 2 h while any two consecutive freeze/thaw cycles must be separated by at least 2 h of thawing period.

In all studied damage functions the definition of critical levels of temperature and moisture content is crucial. In this paper, the critical level of moisture content w_L corresponds with the maximum hygroscopic moisture content of the material in which the point of investigation is placed. It is assumed that when the critical level of moisture content is exceeded, liquid moisture can appear in the pore space of the material making it susceptible to frost damage when exposed to low temperature. The critical temperature T_L can be a matter of further discussion because T_L obviously depends on the pore size distribution of the analyzed material or the possible concentration of soluble salts. Here, a simple assumption is made that moisture in the pore space of the material primarily fills the pores from the smallest to larger ones. Therefore, when cumulative pore size distribution of the material is known, the radius R of the largest saturated pore can be determined